

Please write clearly in block capitals.

Centre number

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Candidate number

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Surname

StemUp Model Solution

Forename(s)

Candidate signature

I declare this is my own work.

A-level PHYSICS

Paper 3

Section B Engineering physics

Monday 17 June 2024

Morning

Time allowed: The total time for both sections of this paper is 2 hours. You are advised to spend approximately 50 minutes on this section.

Materials

For this paper you must have:

- a pencil and a ruler
- a scientific calculator
- a Data and Formulae Booklet
- a protractor.

Instructions

- Use black ink or black ball-point pen.
- Fill in the boxes at the top of this page.
- Answer **all** questions.
- You must answer the questions in the spaces provided. Do not write outside the box around each page or on blank pages.
- If you need extra space for your answer(s), use the lined pages at the end of this book. Write the question number against your answer(s).
- Do all rough work in this book. Cross through any work you do not want to be marked.
- Show all your working.

Information

- The marks for questions are shown in brackets.
- The maximum mark for this paper is 35.
- You are expected to use a scientific calculator where appropriate.
- A Data and Formulae Booklet is provided as a loose insert.

For Examiner's Use

Question	Mark
1	
2	
3	
4	
TOTAL	



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Section B

Answer **all** questions in this section.

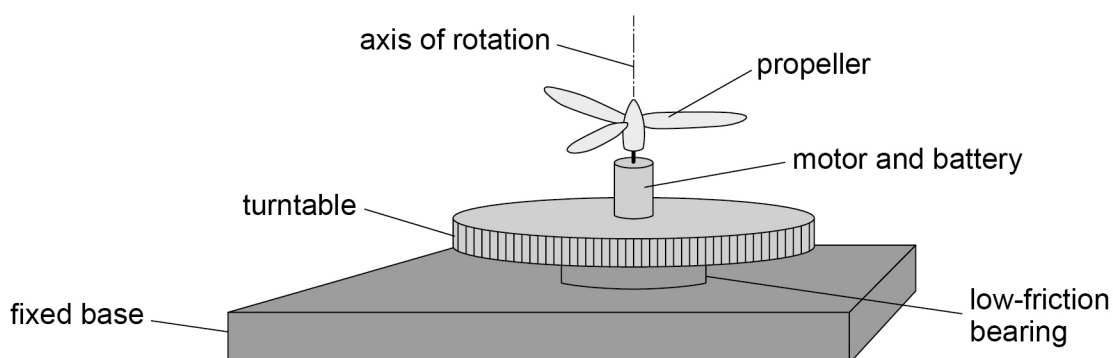
0 1

A heavy turntable is mounted on a fixed base. The turntable can rotate freely on a low-friction bearing.

0 1 . 1

Figure 1 shows a propeller unit fixed to the centre of the turntable. The propeller unit consists of a motor-driven propeller and a battery. The propeller and the turntable have a common axis of rotation.

Figure 1



At first, the turntable and the propeller are at rest.
The propeller motor is switched on and the propeller quickly reaches a high final angular speed.
The propeller rotates clockwise when viewed from above.

Compare, with reference to angular momentum, the motions of the turntable and the propeller.

[3 marks]

No external torque acts on the system, so angular momentum is conserved: the total angular momentum stays zero, as it was at rest at first.

So the angular momentum of the turntable is equal and opposite to that of the propeller ($I_T\omega_T = -I_P\omega_P$), so the turntable rotates anticlockwise (in the opposite direction to the propeller).

The moment of inertia of the turntable is much larger than that of the propeller ($I_T > I_P$), so the turntable rotates much more slowly than the propeller.

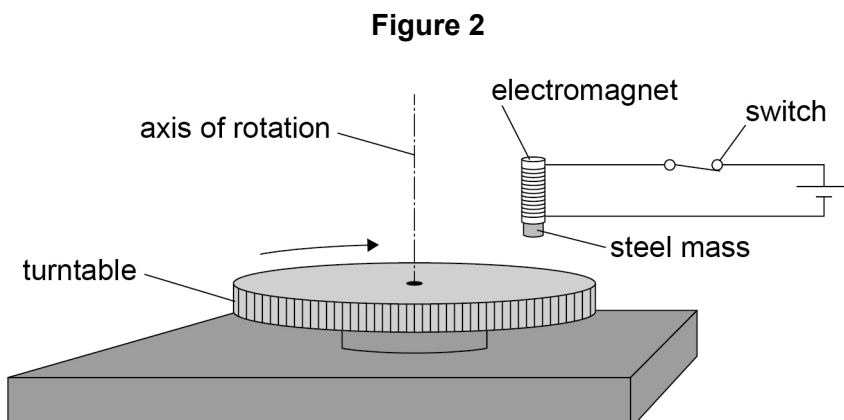
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0 1 2

Figure 2 shows an arrangement used to determine the moment of inertia of the turntable.



A small steel mass is held by an electromagnet above the top surface of the turntable. The diameter of the turntable is about half a metre.

The turntable rotates freely at an initial angular speed ω_1 .

The switch is opened so that the mass falls and sticks to the surface of the turntable. This changes the angular speed of the turntable to ω_2 .

The steel mass can be considered to be a point mass.

Describe how to determine the moment of inertia of the turntable using observations of ω_1 and ω_2 .

In your answer you should:

- suggest how ω_1 and ω_2 are measured
- state any other measurements needed and name the equipment used to make them
- explain how the moment of inertia of the turntable is determined from the measurements.

[6 marks]

Measuring ω_1 and ω_2 : fix a small reflective strip (fiducial mark) to the edge of the turntable and place an optical (light gate) sensor next to it, connected to a datalogger.

The datalogger records the time T for each revolution before and after the mass is dropped. Average over several revolutions, then $\omega = 2\pi/T$ (convert rev s^{-1} to rad s^{-1} by multiplying by 2π).

(Alternatively, film the turntable with a mobile phone video and use frame-by-frame analysis to time several revolutions, or time 10



revolutions of the mark with a stopwatch and divide by 10.)

Other measurements: measure the mass m of the steel mass using a top pan balance. After it sticks, measure the distance r from the centre of the mass to the axis of rotation (centre of the turntable) using a metre ruler (or vernier callipers).

Calculation: the moment of inertia of the point mass about the axis is

$$I_{\text{mass}} = mr^2.$$

No external torque acts as the mass falls vertically, so angular momentum is conserved: $I\omega_1 = (I + mr^2)\omega_2$.

Rearranging: $I(\omega_1 - \omega_2) = mr^2\omega_2$, so $I = mr^2\omega_2 / (\omega_1 - \omega_2)$.

Substitute the measured values of m , r , ω_1 and ω_2 to find I in kg m^2 .

Better: repeat for several different values of r (same m and similar ω_1).

Since $\omega_1/\omega_2 = 1 + (m/I)r^2$, plot ω_1/ω_2 against r^2 : a straight line with gradient m/I , so $I = m / \text{gradient}$.

Repeat each reading and take means to reduce random error; drop the mass from a small height so it does not bounce or slide.



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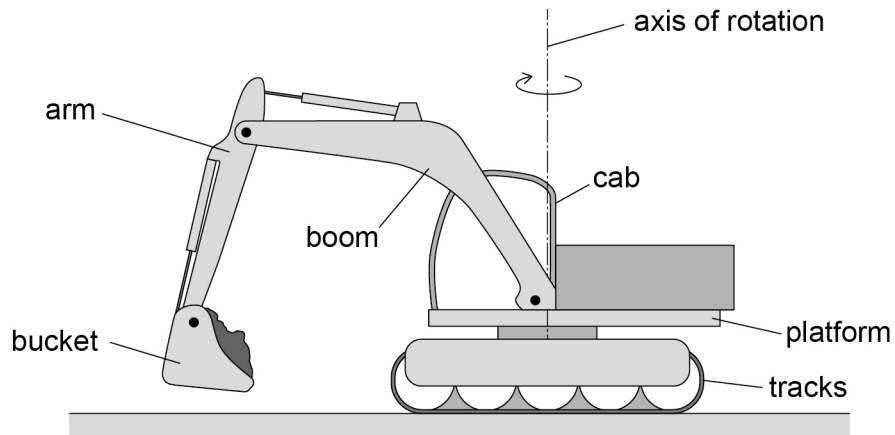
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0 2

Figure 3 shows an excavator.

Figure 3



The bucket position can be changed by moving the boom and arm and by rotating the platform about the vertical axis of rotation.
For the purposes of this question, assume that the excavator tracks do not move.

Question 2 continues on the next page

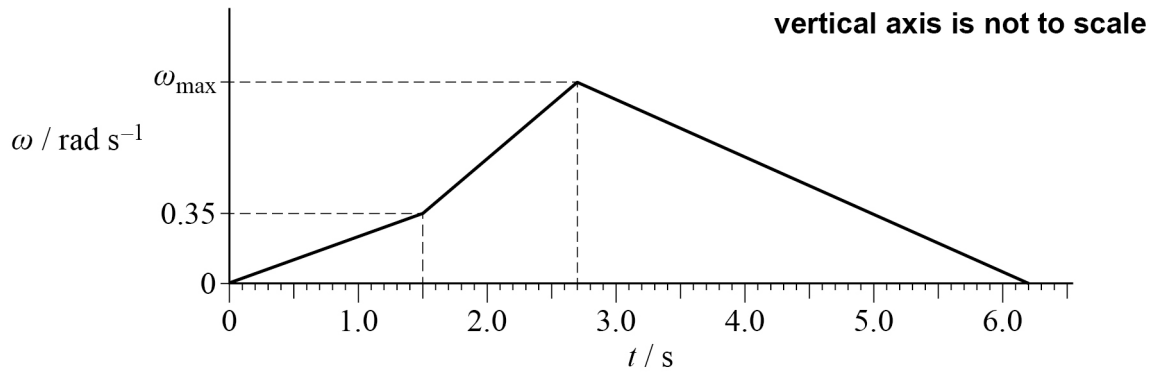
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The bucket is moved to a new position by rotating the platform about the axis of rotation.

Figure 4 shows the variation in angular velocity ω with time t for the rotation of the platform about the vertical axis.

Figure 4



0 2 . 1

The total angular displacement of the platform is 2.52 rad during the movement of the bucket.

Show that $\omega_{\max}$ is about 0.9 rad s^{-1} .

[3 marks]

Angular displacement = area under ω - t graph

$$0 \text{ to } 1.5 \text{ s: } \frac{1}{2} \times 1.5 \times 0.35 = 0.2625 \text{ rad}$$

$$1.5 \text{ to } 2.7 \text{ s: } \frac{1}{2} \times (0.35 + \omega_{\max}) \times 1.2 = 0.21 + 0.60 \omega_{\max}$$

$$2.7 \text{ to } 6.2 \text{ s: } \frac{1}{2} \times 3.5 \times \omega_{\max} = 1.75 \omega_{\max}$$

$$2.52 = 0.2625 + 0.21 + 0.60 \omega_{\max} + 1.75 \omega_{\max}$$

$$2.35 \omega_{\max} = 2.52 - 0.4725 = 2.0475$$

$$\omega_{\max} = 2.0475 / 2.35 = 0.871 \text{ rad s}^{-1} \quad (\approx 0.9 \text{ rad s}^{-1})$$

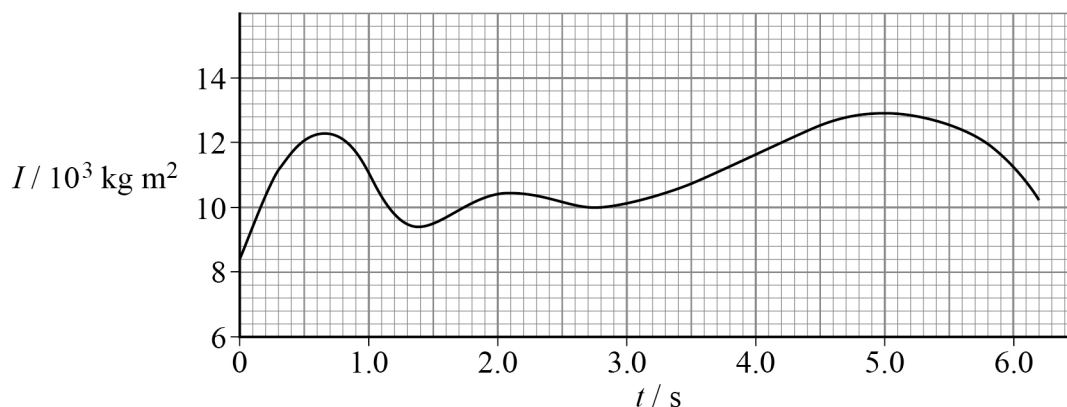


At the same time as the platform is rotating, the bucket is moved up and down, and away from and towards the cab.

The moment of inertia of the rotating parts of the excavator about the axis of rotation is I .

Figure 5 shows how I varies with t for the same time period as **Figure 4**.

Figure 5



0 2 . 2

Torque must be applied to the platform to change its angular velocity and to overcome friction at the platform bearing.

Show that the torque applied to the platform is at a maximum at time $t = 2.1$ s.

[3 marks]

$T = I\alpha$, so T is largest where I and α together are largest.

Use the peak of I in each period ($\alpha = \text{gradient of Fig. 4}$):

0 to 1.5 s: $\alpha = 0.35/1.5 = 0.233 \text{ rad s}^{-2}$

peak $I = 12.2 \times 10^3 \text{ kg m}^2$ ($t = 0.65 \text{ s}$), $T = 12\,200 \times 0.233 = 2850 \text{ N m}$

1.5 to 2.7 s: $\alpha = (0.871 - 0.35)/1.2 = 0.434 \text{ rad s}^{-2}$

peak $I = 10.4 \times 10^3 \text{ kg m}^2$ ($t = 2.1 \text{ s}$), $T = 10\,400 \times 0.434 = 4510 \text{ N m}$

2.7 to 6.2 s: $\alpha = -0.871/3.5 = -0.249 \text{ rad s}^{-2}$

peak $I = 12.8 \times 10^3 \text{ kg m}^2$ ($t = 5.0 \text{ s}$), $T = 12\,800 \times 0.249 = 3180 \text{ N m}$

(this torque is negative: it decelerates the platform)

$4510 \text{ N m} > 3180 \text{ N m} > 2850 \text{ N m}$, so maximum torque is at $t = 2.1 \text{ s}$

Question 2 continues on the next page

Turn over ►



0 2 . 3

Deduce whether the maximum power applied to the platform occurs at the same time of 2.1 s.

[2 marks]

$$\text{At } t = 2.1 \text{ s: } \omega = 0.35 + 0.434 \times 0.6 = 0.61 \text{ rad s}^{-1}$$

$$P = T\omega = 4510 \times 0.61 = 2750 \text{ W}$$

$$\text{At } t = 2.7 \text{ s: } I \approx 10.0 \times 10^3 \text{ kg m}^2, T = 10\,000 \times 0.434 = 4340 \text{ N m}$$

$$P = T\omega = 4340 \times 0.871 = 3780 \text{ W}$$

From 2.1 s to 2.7 s, I is slightly smaller and α is constant, so $T = I\alpha$ is slightly smaller, but ω increases greatly to its maximum.

As $P = T\omega$, P is greater near 2.7 s, so maximum power is not at 2.1 s.

8



Turn over for the next question

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0 3

The Lenoir engine was the first successful internal combustion engine.

Figure 6 shows the basic form of the Lenoir engine. The piston rod drives a crankshaft which is not shown. The fuel is a mixture of gas and air.

Figure 6

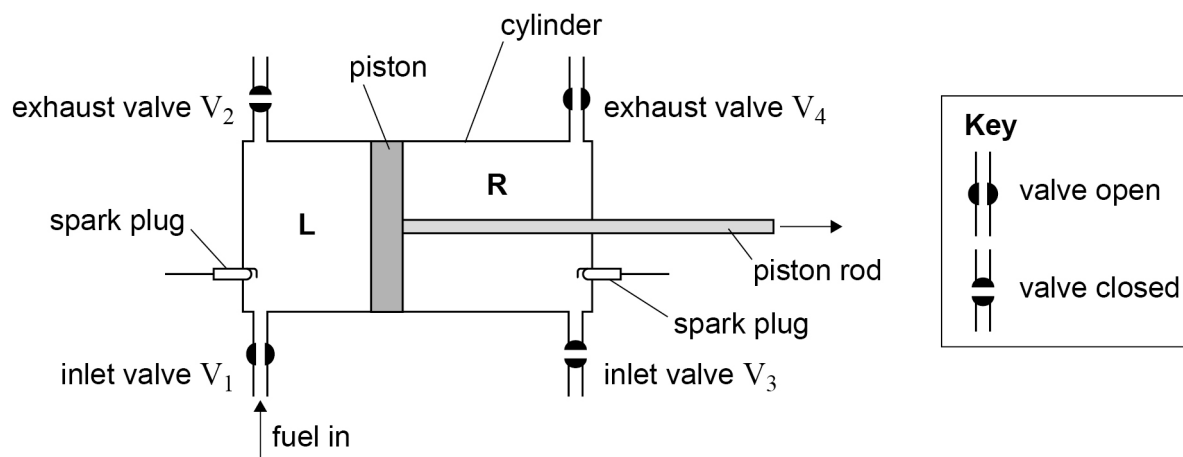
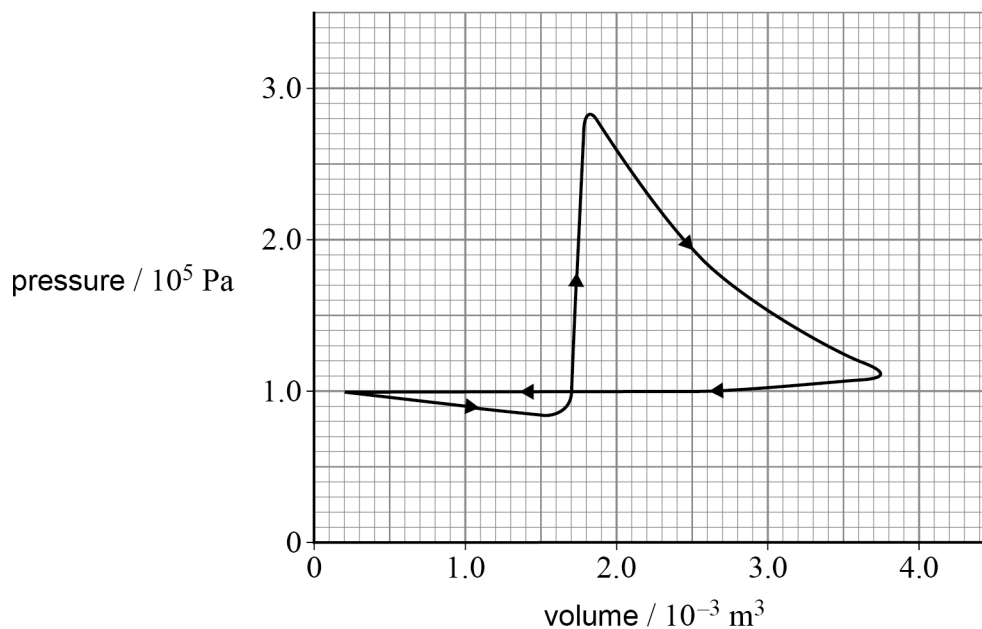


Figure 7 shows an indicator diagram for the space L, taken during a test on a Lenoir engine.

Figure 7



In one cycle the following changes occur in **L**.

- **Induction.** The piston starts at the left-hand end of the cylinder. It moves to the right and fuel passes through the open inlet valve V_1 into **L**. **Figure 6** shows the piston during this induction process, with V_1 open.
- **Ignition.** When the piston is nearly halfway along the cylinder, V_1 is closed. A spark ignites the fuel causing a sudden rise in pressure.
- **Expansion.** The hot gases expand and the piston moves to the end of the stroke.
- **Exhaust.** The exhaust valve V_2 opens. The piston moves to the left. The exhaust gases are expelled at atmospheric pressure.

The same processes are repeated in space **R** one half of a revolution of the crankshaft later than in **L**. So when the piston is moving to the left, induction, ignition and expansion occur in **R** at the same time as the exhaust process occurs in **L**.

0 3 1

The indicator diagram is for a rotational speed of the crankshaft of 120 rev min^{-1} .

Determine, using **Figure 7**, the indicated power of the engine.

Assume that the indicator diagram for **R** is identical to the indicator diagram for **L**.

[5 marks]

Work done per cycle = area of large loop – area of small loop

Large (clockwise) loop ≈ 157 small squares

Small (anticlockwise, pumping) loop ≈ 9 small squares

Net area = $157 - 9 = 148$ small squares

1 small square = $0.10 \times 10^{-3} \text{ m}^3 \times 0.10 \times 10^5 \text{ Pa} = 1.0 \text{ J}$

Net work per cycle = $148 \times 1.0 = 148 \text{ J}$

*$120 \text{ rev min}^{-1} = 2 \text{ rev s}^{-1}$; the engine is double acting (L and R),
so there are $2 \times 2 = 4 \text{ cycles s}^{-1}$*

Indicated power = $148 \text{ J} \times 4 \text{ s}^{-1} = 592 \text{ W}$

indicated power = 592 W

Question 3 continues on the next page

Turn over ►



0 3 . 2

The following data are taken during the test on the engine:

$$\text{fuel consumption} = 6.44 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$$

$$\text{calorific value of fuel} = 18.0 \times 10^6 \text{ J m}^{-3}$$

$$\text{torque at crankshaft} = 39.0 \text{ N m}$$

$$\text{rotational speed} = 120 \text{ rev min}^{-1}$$

Calculate the input power and the output (brake) power of the engine.

[2 marks]

$$\text{Input power} = \text{fuel flow rate} \times \text{calorific value}$$

$$= 6.44 \times 10^{-4} \times 18.0 \times 10^6 = 1.16 \times 10^4 \text{ W}$$

$$\text{Output power} = T\omega, \quad \omega = 2\pi \times 120/60 = 4\pi \text{ rad s}^{-1}$$

$$= 39.0 \times 4\pi = 490 \text{ W}$$

$$\text{input power} = \underline{1.16 \times 10^4} \text{ W}$$

$$\text{output power} = \underline{490} \text{ W}$$

0 3 . 3

The output power of a four-stroke petrol engine of a similar working volume to that of the Lenoir engine is about 150 kW.

Suggest **two** reasons for the very low output power of the Lenoir engine compared with a four-stroke petrol engine.

[2 marks]

1 Power is developed for only about half of the stroke, and the fuel is not compressed before ignition, so the maximum pressure is very much lower than in a petrol engine.

2 The rotational speed of the engine (120 rev min⁻¹) is very low, so there are far fewer power strokes per second; also the pumping loop (negative work) is large compared with the work output loop.



0 3 . 4 Which statement is correct?

Tick (✓) **one** box.

[1 mark]

Thermal efficiency is a measure of how much of the indicated power is converted into output power.

☐

Overall efficiency is the product of mechanical efficiency and thermal efficiency.

☒

Mechanical efficiency is equal to friction power divided by indicated power.

☐

Input power is equal to indicated power plus friction power.

☐

10

Turn over for the next question

Turn over ►



0 4 . 1

The first law of thermodynamics can be expressed by the equation $Q = \Delta U + W$.

State the meaning of each term in this equation.

[2 marks]

Q *energy transferred to the system by heating*

ΔU *increase in internal energy of the system*

W *work done by the system*

0 4 . 2

A system consists of a perfectly insulated room containing only an empty refrigerator. The refrigerator is connected to the mains electricity and the refrigerator door is open.

Deduce, by applying the first law of thermodynamics, whether the internal energy of the room increases, decreases or stays the same.

[3 marks]

$Q = \Delta U + W$. The room is perfectly insulated, so no energy is transferred to or from the room by heating: $Q = 0$.

Electrical work is done on the system by the mains supply (driving the refrigerator), so the work done by the system W is negative.

So $0 = \Delta U + W$ gives $\Delta U = -W$, which is positive, so the internal energy of the room increases (the refrigerator only moves energy around within the room).

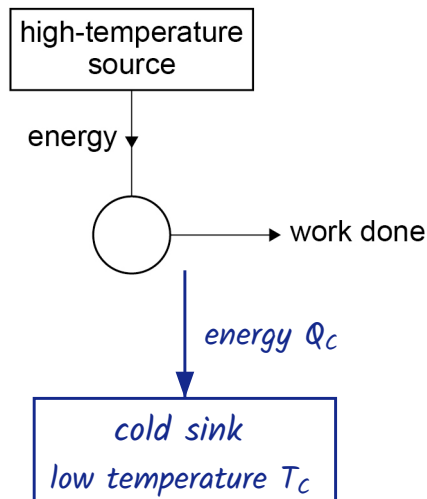


One definition of an ideal heat engine is:

‘a device which provides the maximum possible output of work from a given input of energy by heat transfer.’

Figure 8 shows a heat engine that appears to agree with this definition. The engine takes in energy from a high-temperature source and work is done by the engine.

Figure 8



0 4 . 3 Complete **Figure 8** so that the engine obeys the second law of thermodynamics.

[1 mark]

0 4 . 4 Explain why the maximum theoretical efficiency of an ideal heat engine must be less than 100%.

[2 marks]

The maximum theoretical efficiency is $(T_H - T_C) / T_H = 1 - T_C/T_H$.

This could only be 100% if $T_C = 0$ K, which is impossible, so since $T_C > 0$ the efficiency must be less than 100% (some energy Q_C must always be transferred to the cold sink).

END OF QUESTIONS



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